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A Steam–Gas Power Plant for Combined Generation of Electricity, Heat, and Cold (Trigeneration)

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Abstract—The creation of power plants for combined generation of electricity, heat, and cold is considered. Technical and economic comparative analysis of different ways to accomplish this task is performed on the basis of a special technique developed at the Joint Institute for High Temperatures of the Russian Academy of Sciences. It is shown that on the basis of the existing domestic gas-turbine equipment, power plants for combined generation of electricity, heat, and cold can be created that are significantly superior in their performance to the best technologies in the world.

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INTRODUCTION

With development of the level of technical equipment, new demands of mankind arise, the satisfaction of which becomes a necessity. One of the first demands of humans that became a vital necessity was the demand for heat. Substantially later, the demand for electricity appeared, without which life proper is now inconceivable.

The demand for cold also has long traditions but initially it concerned the problem of foodstuff conservation and was implemented in storing ice or snow in summer time in special refrigerators.

The need for cold to create comfort conditions in rooms has appeared rather recently but also has become one of daily wants already at many locations.

All these needs were satisfied using independent technologies.

A growth in the demand for electricity and heat gave birth to the new more economical technology of their conjoint production.

What induced the necessity of creating the so-called cogeneration?

First of all, it is caused by a low electricity-generation efficiency of steam-turbine electric power stations which reaches 38–39% even in modern steam-turbine plants (STPs).

The main portion of the produced heat in electric-power generation is discharged to the steam-turbine condenser and wasted into the environment through coolers.

A natural desire was to develop a technology that allows to use the condensation heat of water vapors after the steam turbine for the purpose of heat generation for heating needs. In this case the total coefficient of fuel-heat usage (CFHU) on the nominal mode will amount to more than 80% [1–4].

However, it is necessary to pay for every benefit. The steam-turbine power drops in this case from 300 to 250 MW.

As a result, specific capital costs for the heat-and-power station (HPS) increase as compared with the total specific capital expenditures for separate generation of (i) electric power at a condensation power station (state district power station) and (ii) heat at a heating boiler house.

Another HPS disadvantage is the annual irregularity of heat consumption, varying from 100% in the winter period to on the order of 20% for hot-water supply needs with consumer rejection of the heating load.

In this case for maintaining the electric power generation, the main portion of steam is supplied to the condenser, from which the excess heat is discharged into a cooler, while additional capital expenditures appear to be partially “dead.”

With the wide penetration of electricity into life, the need for cold, obtained at the expense of electric power in conditioners, arose. Here, four units of cold are generated in modern conditioners per unit of the electric power spent.

The convenience of modern conditioners is that they also can operate both as a conditioner in the summer months and as a heating device (heat pump) at a negative ambient temperature (the efficiency of which, however, drops as the temperature decreases). It can be assumed that modern conditioners can work as a heat pump only when the air ambient temperature is higher than −10°C.

It should be noted that the specific capital costs for obtaining 1 kW of electric power are 10–15 times higher than those for 1 kW of thermal energy.

Great interest appears in creating refrigeration machines that use thermal energy for cold production. In particular, among them are the absorption lithium–bromide refrigeration machines (ALBRM) [5].

Taking into account that these machines are very bulky and metal-consuming as compared with traditional electric conditioners, it is expedient to use them for high-output centralized cold generation.

Great progress in electric power generation has been achieved in recent years owing to application of promising steam–gas plants (SGPs) with 50–55% efficiency at lower specific capital expenditures.

The doubtless SGPs advantages over STPs, working only for electric-power generation, become less obvious for their operation in the HPS regime.

So, a CFHU reaches 87% at the STP nominal load while for a SGP, it reaches only 82% due to substantial reduction in the thermal-energy generation per unit of the generated electric power. (The portion of the steam-turbine part in a SGP is about 30%.)

An increase in costs of organic fuels, especially oil and gas, has stimulated work on energy saving and energy effectiveness.

In this case, the sharp reduction in the effectiveness of modern HPS operation with a decrease in heat load cannot be ignored, especially because the demand for cold production grows here.

It was natural to attempt the development of a technology for using the HPS discharged energy for cold generation.

The notion "trigeneration"—coproduction of electricity, heat, and cold—has thus appeared.

"Development of engineering solutions for creating optimized systems for simultaneous production of electricity, heat, and cold on the basis of highly effective modular SGPs" was prescribed by the requirement specification in the state contract.

In which way can the optimal system be chosen? What is the criterion for effectiveness?

For that it is necessary (i) to have a certain typical consumer with the specified amounts of electric power, heat, and cold, (ii) to develop several alternative technologies of their production, and (iii) to perform their comparative technical and economic analysis choosing eventually the technology that requires minimum capital and operation expenditures.

It should be noted that if the transport of electric power and heat in the form of hot water can be implemented over fairly large distances and, hence, a consumer can be both centralized and distributed, then the transport of cold is economically justified only for small distances, i.e., a consumer of industrial cold has to be sufficiently major.

As one of these major typical consumers of electricity, heat, and cold, the project of the "Myakininskaya Poima" business center in Moscow can be considered.

The project provides for erection of 14 multistory administrative buildings with the centralized consumption of the following:

—electric power (170 MW);

—thermal energy for heating and hot-water supply (340 MW);

—cold for air conditioning and electronic equipment cooling (200 MW).

The following options were considered as alternative variants:

(1) electric power supply for auxiliaries and for generation of (i) cold using electric conditioners provided by OAO "Mosenergo" and (ii) heat from the Moscow heat network;

(2) electric power supply according to the first variant and creation of the heating boiler house for heat supply;

(3) construction of the prospective binary-cycle SGP for electric-power generation for both internal consumption and cold generation using traditional conditioners, and erection of a heating boiler house for heat supply;

(4) construction of SGP-HPS based on the promising binary-cycle SGPs for trigeneration (combined generation of electricity and heat for both heat supply and cold production using lithium–bromide refrigeration machines installed in each of the 14 project buildings). In this case the heat supplied to each building is used for heating purposes in winter period and for cold production and is extracted from one and the same heating line;

(5) construction of an original developed by authors SGP with steam injection for combined generation of electric power and heat for heat supply and cold production using lithium–bromide refrigeration machines in the same manner as in variant 4.

For reserving the electric power and equalizing electric loads, the electric energy supply is provided from the network of OAO "Mosenergo."

To equalize the heat load and to cover "peak" loads in winter time, a subsidiary water-heating boiler is installed.

Since the objective of the present analysis according to the requirement specification includes determination of the optimal technology for combined generation of electricity, heat, and cold on the basis of modular SGPs rather than a concrete design solution of power supply of the "Myakininskaya Poima" business center, the independent analysis requires a special approach.

In this case, a great number of questions may arise. In particular, what is tariff for electricity from OAO "Mosenergo"? Impartially, it must be higher than the cost of power picked off the terminals of the steam–gas power unit in variant 3 because in the OAO "Mosenergo" system, steam-turbine power units

mainly work, which have higher capital costs and lower efficiency. Additionally, expenditures for transport services of the "Mosenergo" network have to be included in the electric power tariff.

However, a specific character of Russian power generation is such that the statutory tariffs may be lower than the cost of electric power generated at the most modern new electric power station. This is connected with peculiarities of market organization due to the voucher privatization. After the power station became owned for a conventionally low price, the producer could include only operating expenses and a certain benefit into the electric power cost, whereas a private investor building a new power unit must additionally include in the cost the capital consisting of the bank interest for credit and the accelerated amortization, which may be two–three times higher than the operating expenses.

From here contradictions arise. If the price is taken from independent expenditures, then variants 1 and 2 are positioned under obviously disadvantageous conditions; if the price is determined by the underestimated tariff, then variants 3–5 are placed under unfavorable conditions.

It is known that tariffs for heat are higher than the cost of heat generated in water-heating boilers. This paradox is related to using the ill-conceived technique of separating the expenditures for generation of electric power and heat at the HPS.

At the same time, the heat market is most dynamic and unlike the electricity market is not monopolistic.

In connection with the above statements, variants 1 and 2 are excluded from further analysis.

In the creation of trigeneration systems, the main competitive struggle takes place in estimation of cold-generation systems: the traditional system of cold supply by electric conditioners against refrigeration machines that use thermal energy.

Variant 3 is the most effective representative of the first trend.

Indeed, if the matter concerns the creation of new promising power-generation technologies for electric energy production, then now in the world power generation, SGPs are generally recognized, which permit a decrease in capital costs per unit by 25–30% as compared with those of traditional STPs and an increase in the electricity-generation efficiency from 39 to 55%.

Thus, a SGP located in the immediate vicinity of a consumer will provide a minimum cost of electric power.

On the other hand, a cost of thermal energy obtained from the boiler house will also be minimal, in any case, with the now-existing technique of separating expenditures for its production at the HPS, especially without account for expenditures for its transport along the route.

If during the comparative technical and economic analysis, the remaining two variants with trigeneration mentioned above are found to be more effective, then they will all the more retain their advantages under other conditions, which will be easier for them.

The economic effect achieved in this case will be minimal.

Thus, the effectiveness of combined generation of electricity, heat, and cold, as compared with their separated production (advertised in the world power generation), will be estimated by comparing the total expenditures for their generation in variants 3–5 with observing equal conditions and a unified methodological approach.

An original thermal cycle of a SGP for coproduction of electricity and heat has been under development in recent years at the Joint Institute for High Temperatures, Russian Academy of Sciences (JIHT RAS), to make provision for a wide range of consumers of both kinds of energy.

The schematic heat diagram of the proposed SGP modified for operation in the trigeneration system is given in Fig. 1.

The atmospheric air is compressed in the low-pressure compressor *1* and is supplied to the air cooler of mixing type *3*, where it is saturated with water vapors and cooled at the expense of its evaporation.

The compressed air, natural gas, and water vapor are supplied into the SGP combustion chamber *4* in the amounts ensuring the designed temperature of the working fluid before the turbine group of the compressor drive *5*. For cooling the turbine-group elements, water vapor is used, which allows the working-fluid temperature to be increased in excess of the value accepted for the initial gas-turbine plant (GTP) AL-31. In this case the temperature of the blading metal is kept below the design level. With replacement of the coolant of the system for cooling the GTP flow path (from air to steam), the cooling-system construction is fully retained. After expansion in the group of driving turbines, the steam–gas mixture expands additionally in working turbine *7*, where it does useful work, and comes at regenerative heat-exchanger *8*, in which the generation and superheat of the injected steam, as well as the heating of the network water for district heat needs Q_{heat} occur.

After heat-exchanger *8*, the steam–gas mixture expands to atmospheric pressure in expander *9*; in this case useful work is done and an additional amount of water is condensed, which is trapped in drop-moisture separators *10*. After separators *10*, dehydrated combustion products are discharged into the atmosphere.

Together with the main condensate flow from heat exchanger *8*, the water from separators *10* enters the air cooler of mixing type *3*, then comes at purification system *11*, from where it makes its way to heat exchanger *8* for steam generation and superheat. The excess amount of water condensed from combustion products may be used for any purpose. The heat of water vapor condensation released in heat exchanger *8*

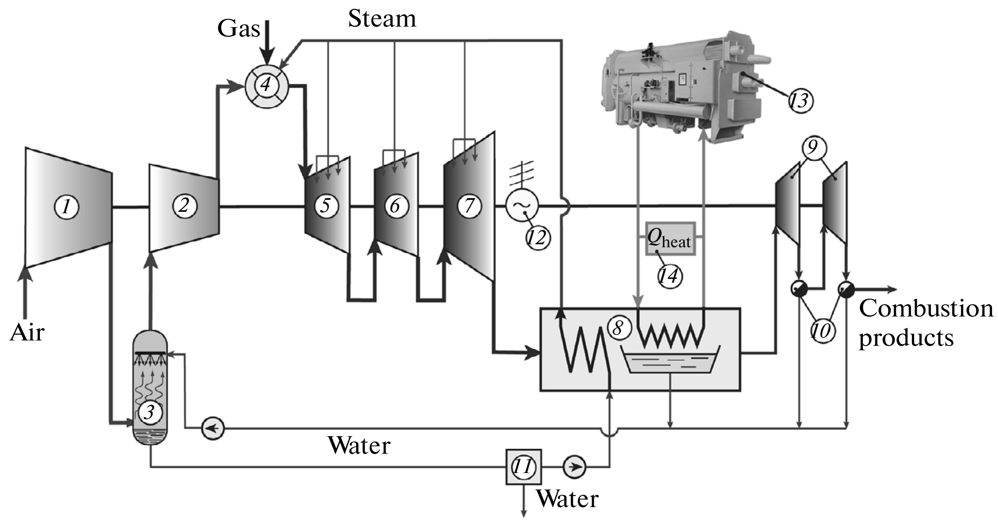

Fig. 1. The schematic heat diagram of the SGP for coproduction of electricity, heat, and cold: low-pressure compressor (*1*); high-pressure compressor (*2*); mixing-type air-cooler (*3*); combustion chamber (*4*); high-pressure driving turbine (*5*); low-pressure driving turbine (*6*); power turbine (*7*); regenerative heater (boiler-utilizer) with the heater of water from the water-supply network (*8*); steam-air turbo-expander (*9*); separator of moisture drops (*10*); system of condensate purification and cycle water preparation (*11*); electrical generator (*12*); ALBRM aggregate (*13*); typical heat consumer (system of centralized heat supply) (*14*).

is transferred to a typical heat consumer *14* and also is channeled for cold production needs in ALBRM *13* over general lines of the standard heat network.

We enumerate the main advantages of the proposed technology.

(1) Based on the existing domestic aviation engine AL-13 with a power of 20 MW, a steam–gas power plant can be created with steam injection having an electric power on the order of 80–100 MW both at the expense of an increase in the degree of GTP compression and due to the steam injection into the gas path.

(2) The condenser of steam from the steam–gas mixture after the power gas turbine works under an excess pressure of 0.35–0.45 MPa, which makes it possible to condense all injected steam from the steam–gas mixture and to create a closed water-supply system with obtaining the hot network water at a temperature on the order of 100°C for needs of heat supply or cold production.

(3) The dehydrated steam–gas mixture expands in the turbo-expander with cooling down to a temperature on the order of 40°C and condensation of water vapors formed in the process of burning of fuel (methane) hydrogen, which ensures the achievement of the efficiency of electricity generation on the heat consumption with the lowest heating value and the CFHU substantially exceeding 100%.

(4) As compared to traditional binary-cycle SGPs operating in the HPS regime, the heat generation per unit of produced electric power grows by more than 70%, which allows the extension of the operation range in the cogeneration system with an increase in the heat load without using peak-load boilers.

(5) Unlike all types of power plants, the level of temperatures of the low-potential heat taken away from the condenser of the steam–gas mixture at all seasonal heat loads is 90–100°C. The plant is best suited to provide the ALBRM systems with a hot coolant for cold production without additional expenses in the case of reduction in heat consumption for heating needs; i.e., it can work year-round in the regimes close to nominal.

(6) The steam injection to the GTP combustion chamber apart from the increase in the gas turbine power enables the nitric oxide content in the SGP smoke to be reduced down to several ppm (experimentally confirmed); i.e., it allows the plant to be ecologically pure.

RESULTS OF THE COMPARATIVE TECHNICAL–ECONOMIC ANALYSIS

As has been mentioned above, three alternative variants (3–5) are considered for power supply of a certain closed region (conventionally, the "Myakininskaya Poima" business center in Moscow).

For more correct determination of the capital and operation expenditures in choosing the type of binary-cycle SGP, the existing plants were used.

A fractional number of plants was used for meeting the needs.

Figure 2 displays a plot of the annual heat loads for the binary-cycle SGP-HPS (variant 2). Figure 3 presents the appropriate heat-load plot for the SGP of JIHT RAS.

Basic data of the compared alternative variants are given in the table.

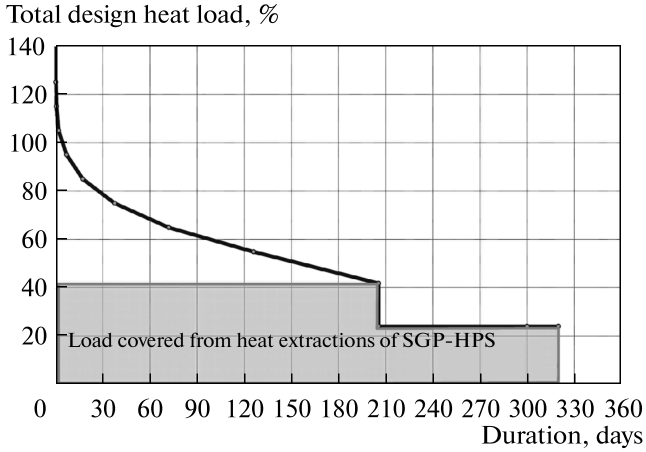

Fig. 2. The relation of heat loads covered at the expense of the main power-generation plant and boiler house (variant 2).

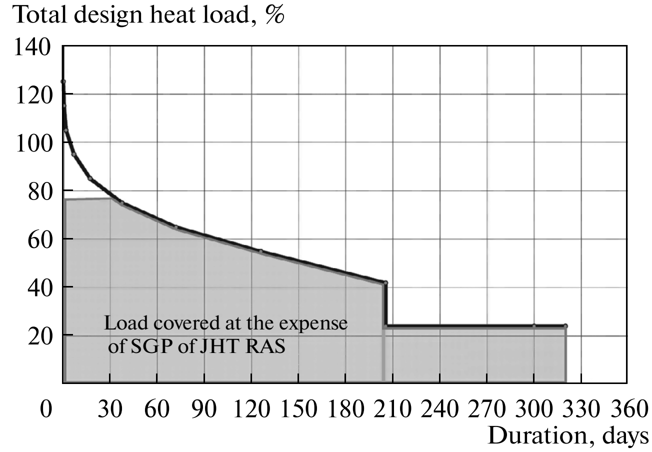

Fig. 3. The relation of heat loads covered at the expense of the main power-generation plant and boiler house (variant 3).

While determining the capital expenditures, a special technique developed at JIHT RAS was used that was applied successfully in works within the collaboration with the United States [6].

The basic essence of the technique used is the line-by-line juxtaposition of the typical structure of capital costs of the etalon power stations of the Soviet Union and the United States with 300-MW power units and

Table

Variants under consideration	SGP + boiler house + conditioners	SGP-HPS + boiler house + ALBRM	SGP of JHT RAS + boiler house + ALBRM
Electric power, MW:			
—for general needs	220.0	220.0	220.0
—for cold production	40.8		
—in total	260.8	220.0	220.0
Thermal power, MJ/s:			
—in winter maximum for needs of heat supply and hot-water supply	400.0	400.0	400.0
—in summer maximum, in total	96.0	273.0	273.0
including for hot-water supply needs	96.0	96.0	96.0
including for cold production		177.0	177.0
Calculation of the number of plants			
Main power generation plant, MW:			
—installed capacity	230	230	70
—useful power in the nominal regime	221.0	212.5	70.1
—useful power in the summer period	206.9	200.8	61.8
Conventional design number of power generation plants	1.261	1.096	3.560
Boiler plants			
Thermal power of the main power-generation plant, MJ/s:			
—of a single plant	0	160.5	87.5
—total capacity for all power-generation plants	0	175.8	311.5
The boiler plant power, MJ/s	400.0	224.2	88.5
Conventional design number of water-heating boilers	3.439	1.927	0.761
Total capital expenditures in millions of US dollars	405.4	364.8	305.7
including:			
—for main power-generation plants	329.9	296.1	253.6
—for boiler houses	49.1	27.5	10.9
—for cold-production plants	26.4	41.3	41.3

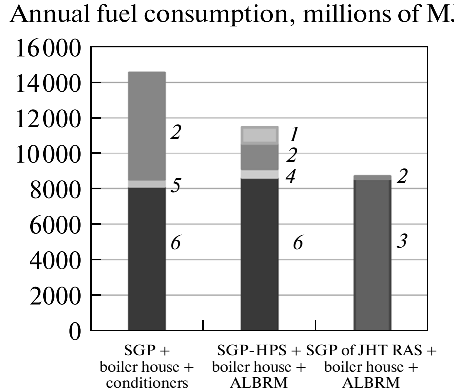

Fig. 4. The total annual fuel consumption for variants and its distribution over the kinds of generated power: for heat production for ALBRM (*1*); for heat to the boiler house; total consumption for the SGP of JHT RAS (*3*); for heat at SGP-HPS (*4*); for cold (*5*); for electrical power (*6*).

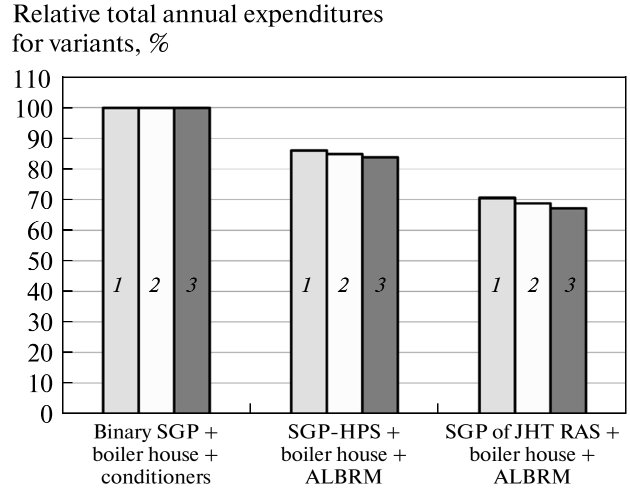

Fig. 5. Relative total annual expenditures with a gas cost of \$120/1000 m^3 (*1*); \$200/1000 m^3 (*2*); \$300/1000 m^3 (*3*).

the proposed alternative technologies with the simultaneous statistical processing of world prices for the basic nonstandard equipment.

All data in this case are expressed in fractions of specific capital costs of an etalon steam-turbine power station.

At the level of the year 2013, specific capital investments in etalon are accepted in the amount of 1500 US per 1 kW of established power.[1]

Figure 4 presents the results of calculations of annual fuel (natural gas) consumption.

The calculation of the total annual expenditures for all variants was assumed from the terms of work under market conditions with the following prerequisites:

– the payback period of capital expenditures for the higher investor is 10 years from the beginning of construction (accelerated amortization);

– 50% capital expenditures are implemented at the expense of the share capital with dividends of 14% per annum; 50% capital expenditures are the borrowed funds under the bank credit in amount of 10% per annum;

– redemption of the share capital starts after repayment of the credit;

– the fuel cost varies within the limits of \$120/1000 m^3, \$200/1000 m^3, and \$300/1000 m^3;

– operating conditions of the plants after the initial capital repayment are not considered at the given stage.

Figure 5 presents the comparative data on the total annual expenditures for the compared variants.

CONCLUSIONS

(1) The power generation plants for combined production of electricity, heat, and cold that substantially surpass those of the best technologies in the world in their characteristics can be created on the basis of the existing domestic gas-turbine equipment.

(2) The annual saving of energy resources may be up to 24% in comparison with the SGP-HPSs on the basis of foreign GTPs and up to 38% as compared to the variant of separated production of (i) electricity based on the promising binary-cycle SGPs, (ii) heat on the basis of hot-water boilers with an efficiency of 92%, and (iii) cold using modern electric conditioners.

(3) The total annual expenditures for the variant of electricity, heat, and cold combined generation on the basis of SGP of JIHT RAN are 30% lower than in their separate production and more than 20% less than in their combined generation on the basis of the prospective SGP-HPSs based on the binary-cycle SGP.

(4) The SGP of JIHT RAN proposed for implementation is ecologically pure because the content of toxic nitric oxides in smoke is reduced by several times as compared with that of modern SGPs, while carbon dioxide discharges per 1 kW h of the generated electric power decrease by more than 20–30%.

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